COMPUTATIONAL INVESTIGATION OF PLASMA-WALL INTERACTION ISSUES IN MAGNETIZED TARGET FUSION

Peter Sheehey, Walter Atchison, Rickey Faehl,
Ronald Kirkpatrick, Irvin Lindemuth, and Richard Siemon
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

Abstract

In the concept known as Magnetized Target Fusion (MTF) in the United States and Magnitnoye Obzhatiye (MAGO) in Russia, a preheated and magnetized target plasma is hydrodynamically compressed to fusion conditions. Because the magnetic field suppresses losses by electron thermal conduction in the fuel during the target implosion heating process, the implosion velocity may be much smaller than in traditional inertial confinement fusion. Hence "liner-on-plasma" compressions, magnetically driven using relatively inexpensive electrical pulsed power, may be practical. The relatively dense, hot target plasma, with starting conditions O(10^{18} cm^{-3}, 100 eV, 100 kG), may spend 10 or more microseconds in contact with a metal wall during formation and compression. Influx of a significant amount of high-Z wall material during this time could lead to excessive cooling by dilution and radiation that would prevent the desired near-adiabatic compression heating of the plasma to fusion conditions. Magnetohydrodynamic (MHD) calculations including detailed effects of radiation, heat conduction, and resistive field diffusion are being done, using several different computer codes, to investigate such plasma-wall interaction issues in ongoing MTF target plasma experiments and in proposed liner-on-plasma MTF experiments.

I. INTRODUCTION

Magnetized Target Fusion (MTF) is an approach to controlled fusion that is intermediate between magnetic confinement and inertial confinement fusion (ICF) in time and density scales. Bigger targets and much lower initial target densities than in ICF can be used, reducing radiative energy losses. Reduced losses permit near-adiabatic compression of the fuel to ignition temperatures, even at low (e.g., 1 cm/μsec) implosion velocities. In MTF, the convergence ratio ($r_{initial}/r_{final}$) of the pusher in quasi-spherical geometries may potentially be less than 10, depending upon the initial temperature of the fuel and the adiabaticity of the implosion. Therefore, "liner-on-plasma" compressions, magnetically driven using relatively inexpensive electrical pulsed power, may be practical [1-4].

An MTF system requires two elements: (1) a preheated and magnetized initial "target" plasma; (2) a target implosion driver. Because the reduced energy losses in MTF relax the power and intensity requirements for an implosion driver, an optimal driver source for MTF might be relatively inexpensive electrical pulsed power, to drive a liner-on-plasma implosion. This could utilize either fixed pulsed-power facilities, such as the Pegasus and Atlas capacitor banks at Los Alamos and Shiva-Star capacitor bank at the Air Force Weapons Laboratory (Albuquerque), or explosive-flux-compression generators, such as Los Alamos' Procyon or the Russian 200-MJ-class disk flux compression generators [3,4]. Such energy-rich sources might allow a demonstration of fusion ignition via MTF, without a major capital investment in driver technology.

The success of magnetized target fusion will depend upon a number of issues. The initial target plasma must meet minimum temperature (~50 eV, preferably 100-300 eV), density (between 10^{-3} and10^{-6} g/cm^3), and magnetic field (>50 kG) requirements, and must have a lifetime, adjacent to the supporting wall, greater than the implosion time (typically several μsec for a pulsed-power-driven implosion). Plasma-wall interaction must not create dynamical effects or excessive introduction of impurities, which might lead to rapid cooling of the plasma. The target plasma must be readily integrable with drivers for compression to fusion conditions. As it implodes, the liner must remain sufficiently intact that it can effectively compress the target plasma.

Los Alamos National Laboratory (LANL) and the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) have pursued MAGO/MTF research in recent years [3-12]. Los Alamos is presently investigating three candidate target plasmas: the Russian-originated, explosive-pulsed-power-driven MAGO plasma formation scheme, the high-density Z-pinch, and the Field Reversed Configuration (FRC), an elongated compact toroid. MAGO work includes ongoing joint US-Russian experiment and theory aimed at determining the suitability of the plasma created for MTF compression. A partially wall-supported deuterium-fiber-initiated Z-pinch experiment at LANL has been investigated for MTF applications. Los Alamos is now beginning experimental and theoretical investigation of an FRC plasma for MTF compression.

Related experimental and computational work aims to evaluate explosive-flux-compression generators and existing pulsed power facilities as MTF liner drivers. A joint LANL-VNIIEF experiment (high energy liner

0-7803-5498-2/99/$10.00©1999 IEEE.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	-

4. TITLE AND SUBTITLE
Computational Investigation Of Plasma-Wall Interaction Issues In Magnetized Target Fusion

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Los Alamos National Laboratory Los Alamos, NM 87545 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
In the concept known as Magnetized Target Fusion (MTF) in the United States and Magnitnoye Obzhatiye (MAGO) in Russia, a preheated and magnetized target plasma is hydrodynamically compressed to fusion conditions. Because the magnetic field suppresseslo sses by electron thermal conduction in the fuel during the target implosion heating process, the implosion velocity may be much smaller than in traditional inertial confinement fusion. Hence liner-on-plasma compressions, magnetically driven using relatively inexpensive electrical pulsed power, may be practical. The relatively dense, hot target plasma, with starting conditions O(lO* cmJ, 100 eV, 100 kG), may spend 10 or more microseconds in contact with a metal wall during formation and compression. Influx of a significant amount of high-Z wall material during this time could lead to excessive cooling by dilution and radiation that would prevent the desired near-adiabatic compression heating of the plasma to fusion conditions. Magnetohydrodynamic (MHD) calculations including detailed effects of radiation, heat conduction, and resistive field diffusion are being done, using several different computer codes, to investigate such plasma-wall interaction issues in ongoing MTF target plasma experiments and in proposed liner-on-plasma MTF experiments.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

"HEL-1") executed in August, 1996, put approximately 100 MA through a 24-cm-radius, 4-mm-thick, 10-cm-long aluminum cylindrical liner, which, by the time it reached the 5.5 cm radius of the central measuring (diagnostic) unit (CMU), was imploding at 7 mm/μsec and contained approximately 20 MJ of kinetic energy [7,8,11,12]. Such a liner approaches the energy and velocity regime required to drive an MTF target such as MAGO to fusion conditions. Recent liner experiments at Shiva-Star (e.g., Faehl, et al., reported at this conference) also demonstrate liner performance suitable for some MTF target plasmas.

In this paper, we describe computational modeling of proposed cylindrical liner-on-plasma compressions of such target plasmas with such liner systems. Computational models of the MAGO target plasma and the HEL-1 liner have shown good agreement with experiment [5-12]. These computational models provide good starting points for liner-on-plasma simulations. The results of such liner-on-plasma simulations can point out important issues which must be confronted in designing such experiments.

II. COMPUTATIONS

Two Los Alamos MHD codes have been employed in modeling MTF experiments. The MHRDR code has been used extensively in modeling the MAGO and fiber-initiated Z-pinch target plasma experiments (13). Because MHRDR is fully implicit and has a generalized Eulerian structure, in which zonal quantities such as velocity are computed relative to a pre-programmable grid velocity, the code can run liner-on-plasma calculations relatively quickly. However, it can only compute a single material (e.g., the target plasma DT); the outer radial boundary of the computational mesh is programmed to implode at the expected liner velocity. Boundary conditions are idealized: perfectly electrically conducting and zero-temperature, infinitely heat-conducting walls (hence the heat conductivity of the magnetized plasma is the only impediment to heat flow out the boundary). In these cases MHRDR uses cylindrical r-z geometry with a single B_θ magnetic field component. The plasma radiative energy losses and electrical resistivity are taken from Los Alamos "Sesame" data tables. Heat conduction is full (arbitrary $\omega_\alpha\tau_\alpha$) Braginskii, unless we override this for comparison to other models.

A second Los Alamos Eulerian MHD code [14] was used to model the HEL-1 and Shiva-Star liner experiments. This code can compute multiple materials, such as an aluminum liner imploding onto a DT plasma. However, it runs much slower than MHRDR because it is not fully implicit and must use a fixed grid; to date it has only been possible to do one-dimensional liner-on-plasma calculations (two-dimensional runs are planned). At present, Braginskii heat conduction is only included for the electron fluid (ion fluid has the non-magnetized conductivity value); however, it has been possible to estimate the Braginskii effect on the ions and include a constant factor times the non-magnetized value (1/15) to approximate the full Braginskii magnetoinsulation effect. Braginskii ion heat conduction is being added to this code. The diffusion of magnetic field, heat, and radiation between liner and plasma is computed, but the boundary between liner and plasma remains sharp (i.e., no intermixing takes place).

A one-dimensional liner-on-plasma problem based on demonstrated target plasma and liner drive quantities was run with both codes. The target plasma resembled a late-time (smaller chamber) MAGO plasma: 100 eV, 10^{-5} g/cm^3, with 3.0 MA on the 1.0 cm-radius copper inner conductor, with the outer aluminum liner starting at 5.4 cm inner radius (0.6 cm thick). The current driving this liner was based on a portion of the measured HEL-1 current, which would implode this liner from 5.4 cm to 1.36 cm in 7.5 μsec, with a final implosion velocity of 1.6 cm/μsec (computed liner inner radius vs. time values were used in the MHRDR calculation). Such a liner implosion is not an optimized choice for an experiment intended to achieve fusion conditions, but it represents something clearly achievable, and which could serve as a useful step in demonstrating compression heating of an MTF plasma.

For an equivalent volumetric adiabatic compression (cylindrical), the temperature of the gas would go from 100 eV to 1.03 keV. The MHRDR one-dimensional, two-temperature calculation, which includes radiative and conductive heat losses, reaches a mass-weighted average temperature ($<T_i>\sim<T_e>$) of 620 eV, with a final radial temperature profile peaking at 900 eV (Figure 1). The final radial density profile is relatively flat, about $3X10^{-4}$ g/cm^3, except for higher values adjacent to the cold walls, particularly the imploding wall. Pressure is peaked similarly to temperature, while magnetic field is the inverse of this. A MHRDR three-temperature calculation, starting with a radiation temperature of 1 eV, with open boundaries, duplicates this result, confirming our assertion that the DT plasma is optically thin, so that two-temperature calculations with a radiative energy loss term are sufficient. A two-temperature MHRDR calculation, with Braginskii electron heat conduction and non-magnetized ion heat conduction multiplied times an arbitrary factor of 1/15, also gave a final peak temperature of 900 eV; this multiplier was then used in calculations with the other code to approximate the Braginskii ion insulation effect.

Calculations with the second code show similar final plasma conditions in the target plasma, although the peak temperature reached is slightly under 800 eV, compared to the idealized MHRDR case 900 eV. Figures 2 and 3 show radial temperature and current distribution in the inner rod, target plasma, and liner, at a time slightly later than the MHRDR profiles in Figure 1. Note the substantial diffusion of heat and field into the inner and outer metal walls, leading to wall temperatures as high as 40 eV. Also note that plasma pressure is high enough

that the inner rod has been compressed from its initial radius of 1.0 cm to about 0.93 cm.

MHRDR has also been used to compute one- and two-dimensional compressions of computed late-time MAGO target plasmas at 2 cm/μsec. The starting conditions for these calculations were computed second-chamber plasmas at 12 μsec in the LANL-VNIIEF MAGO-2 target plasma experiment; the MAGO-2 target plasma calculations showed good agreement to the earlier time experimental measurements available [7-11]. The computed late-time MAGO plasma profiles are diffuse, wall-supported Z-pinch equilibria which show Kadomtsev stability to m=0 perturbations. In liner-on-plasma calculations, the 10-cm outer wall was imploded at 2 cm/μsec to a final radius of 1.4 cm (inner wall was 1.2 cm). One-dimensional calculations reached a peak mass-weighted average temperature of 4.75 keV, with a peak profile temperature of 7 keV. Two-dimensional calculations have been run as far as 3.5 μsec to date, with the <T> the same as in the one-dimensional result (800 eV). An interesting feature can be seen in the two-dimensional calculation: formation of convective cooling cells close to the imploding outer boundary (Figure 4). The MHRDR code has previously been used in studies of such cells [15-17]. Since the bulk temperature reached has not changed compared to the one-dimensional case, this appears (to the time calculated to date) to be a localized effect countered by stronger heating and insulating processes.

Will ionized wall material mix with and cool DT plasma before it can be compressively heated to fusion conditions and produce significant fusion energy? The answer to this question depends upon the rates of the competing processes of implosion, heating, mixing, and cooling. Detailed calculations, which must ultimately be validated by experiment, can answer this question. The codes described here contain substantial portions of the physics governing these competing processes, including potential two-dimensional effects. Guided by experimental data as it becomes available, we can utilize these tools to predict the important issues for optimizing the design of future MTF liner-on-plasma demonstration experiments.

III. CONCLUSIONS

Magnetized Target Fusion (MTF) is an approach to controlled fusion which potentially avoids the difficulties of the traditional magnetic and inertial confinement appoaches. It appears possible to investigate the critical issues for MTF at low cost, relative to traditional fusion programs, utilizing pulsed power drivers much less expensive than ICF drivers, and plasma configurations much less expensive than those needed for full magnetic confinement. Computational modeling of separate MTF target plasma and liner implosion experiments has shown good agreement to experiment. Combining target plasma and liner implosion computational models allows detailed theoretical investigation of important issues for proposed MTF liner-on-plasma experiments.

IV. REFERENCES

1. I. Lindemuth and R. Kirkpatrick, Nuclear Fusion 23, 263 (1983).
2. V. Mokhov et al., Sov. Phys. Dokl. 24, 557 (1979).
3. V. Chernyshev et al., in Megagauss Fields and Pulsed Power Systems, ed. V. Titov & G. Shvetsov, p. 347, Nova Science Publishers, NY(1990).
4. A. Pavlovskii et al., ibid., p. 327.
5. V. Chernyshev et al., in Megagauss Magnetic Field Generation and Pulsed Power Applications, ed. M. Cowan and R. Spielman, Part 1, p. 557, Nova Science Publishers, New York (1995).
6. I. Lindemuth et al., ibid., p. 361.
7. P. Sheehey et al., in Megagauss-VII Proceedings, Sarov, Russia (1996).
8. R. Reinovsky et al., ibid.
9. I. Lindemuth, V. Chernyshev, V. Mokhov et al., Physical Review Letters 75(10), 1953 (1995).
10. P. Sheehey et al., Fusion Technology 30, 1355 (1996).
11. P. Sheehey et al., in Megagauss-VIII Proceedings, Tallahassee, FL (1998).
12. R. Faehl et al., in Proceedings of the 11th International Pulsed Power Conference, Baltimore, MD, p. 1375 (1997).
13. P. Sheehey and I. Lindemuth, Physics of Plasmas 4, 146 (1997).
14. R. Bowers et al., J. Appl. Phys. 83, 4146 (1998).
15. I. Lindemuth and T. Jarboe, Nuclear Fusion 18, 929 (1978).
16. I. Lindemuth et al., Physics of Fluids 21, 1723 (1978).
17. P. Sheehey et al., in Dense Z-Pinches, 4th International Conference, AIP Conference Proceedings 409, p.17 (1997).

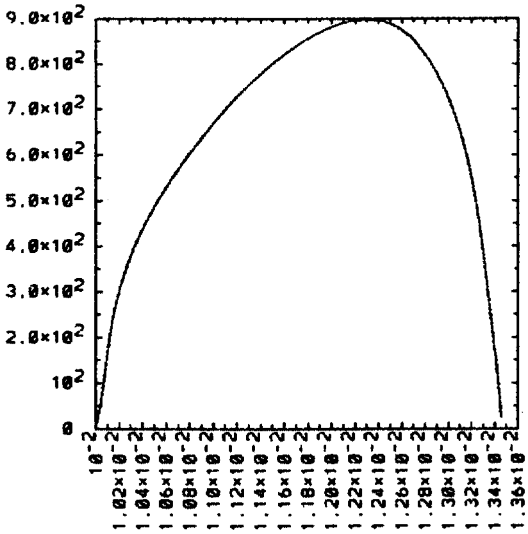

Figure 1. Temperature (eV) vs. radius (m.), MHRDR 1-d calculation.

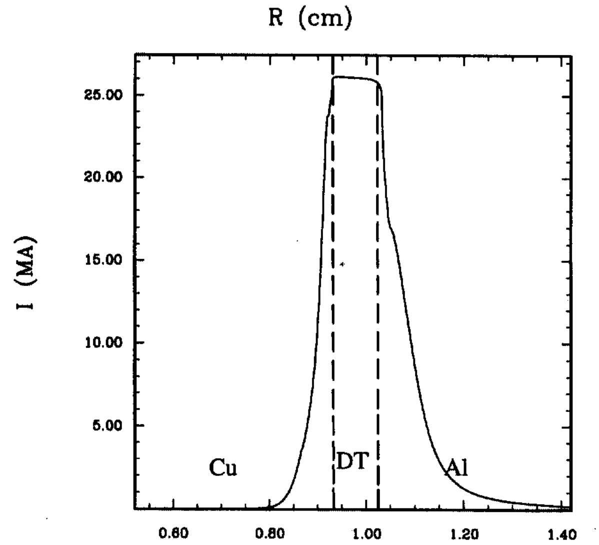

Figure 3. Current (MA) vs. radius (cm.), second code 1-d calculation.

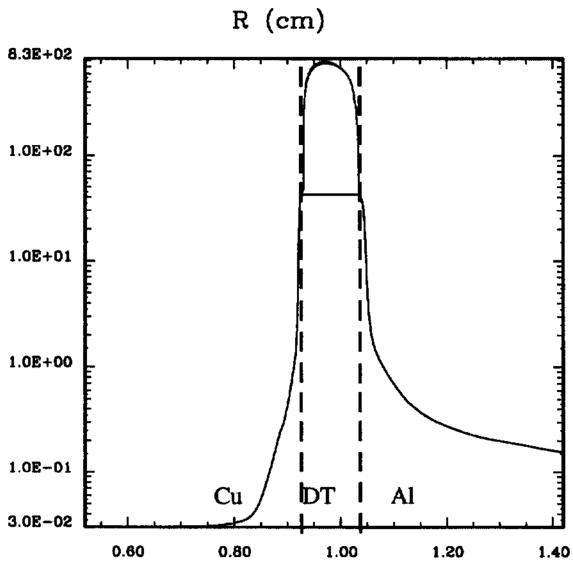

Figure 2. Temperature (eV) vs. radius (cm.), second code 1-d calculation.

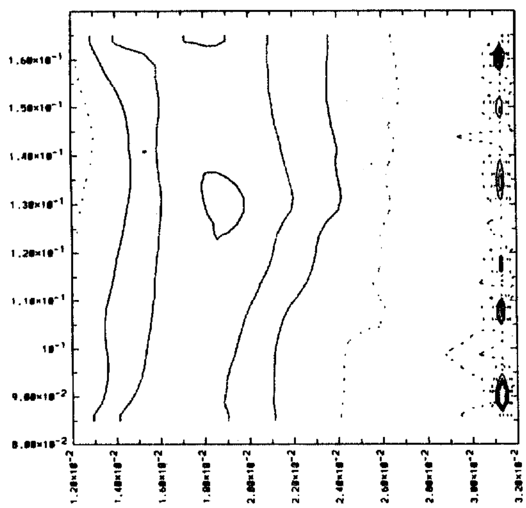

Figure 4. Mass density (kg/m^3) contours, MHRDR 2-d calculation, time 3.4 μsec; first solid line adjacent to dotted lines represents 4.55X10^{-2} kg/m^3, other solid lines each 20% higher, dotted 20% lower.